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An Advanced Study on the Development of Marine Lifting Devices Enhanced by the Blowing Techniques

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Abstract

High lifting devices used for control purposes have received much attention in the marine field. Hydrofoils for supporting the hull, roll stabilizer fins for developing the motion damping performance, rudders for maneuverability are the well-known devices. In the present study, the ability of the rudder with flap to produce high lift was analyzed. The boundary layer control, one of the flow control techniques, was adopted. Especially, to build the blown flap, a typical and representative type of a boundary layer control, a flapped rudder was designed and manufactured so that it could eject the water jet from the gap between the main foil and the flap to the flap surface tangentially. And it was tested in the towing tank. Simultaneously, to know the information about the 2-dimensional flow field, a fin model with similar characteristics as the rudder model applicable for the motion control was made and tested in the cavitation tunnel. In addition, local flow measurements were carried out to obtain physical information, for example, a surface pressure measurement and flow visualization around the flap. And CFD simulation was used to obtain information difficult to collect from the experiment about the 2-dimensional flow.

Keywords: coanda effect, high lifting device, water jet ejection, rudder, fin

1 Introduction

Because modern ships, including the submarines, have been traditionally large moving at low speeds, ensuring maneuverability and control have become important problems in their initial design stage. When jet flow is ejected on a surface tangentially, it might flow along the surface due to the pressure difference around the surface; this phenomenon is widely known as the Coanda effect. Therefore, a separation flow control using the above physical effect is adopted to obtain high lift in the marine control surfaces. To understand the effect of high lift, we need to observe the change in the flow field due to water jet ejection on the control surfaces. When jet flow is ejected, the lift, the form drag, and the moment change. At this time, the information about the physical characteristic changes of flow filed becomes very important and need to be understood. Above all, because research efforts in the marine field have not been reported in the literature to the author's knowledge, we studied the flapped rudder, which is used to keep a ship on course. We tried to develop a rudder with reinforced lifting performances.

In addition, the flow characteristics in uniform flow of 2-dimensional section must be understood. Simultaneously, the physical effect of the boundary layer control and circulation increase by the water jet ejection on the lift or drag characteristics must be also understood. Therefore, a 2-dimensional fin model was prepared, installed, and tested in the cavitation tunnel. The changes of lift and drag affected by the water jet ejection were investigated, and the equivalent lift-drag ratio accounting for the water pump consumption power was investigated to evaluate the efficiency about the lift increase versus jet ejection.

The local flow field was observed and measured to understand the physical phenomena around the flap. Also, the physical phenomena difficult to observe from experiments were investigated in detail by CFD simulation.

The above- mentioned experimental study showed that high lift produced by flow control can be applied to marine control surfaces.

2 Apparatus & test

2.1 Towing test of rudder

The NACA0021 section, widely known as a typical rudder section, was selected as a model for this case and a flap was installed (Ahn and Kim 1999). Table 1 shows the detailed dimensions of the rudder, and figure 1 shows the fully composed model.

Table 1: Principal dimensions of rudder

NACA0021	Main Foil	Flap
1. Chord (mm)	300	122 (30.5%C)
2. Span (mm)	600 (M. Part : 300)	600 (M. Part : 300)
3. Position of sensor: 30%c from L.E.		
4. Position of flap hinge: 25%c from T.E.		
5. Maximum thickness: 21%c		
6. Geometric aspect ratio: 1.5 & 0.75		

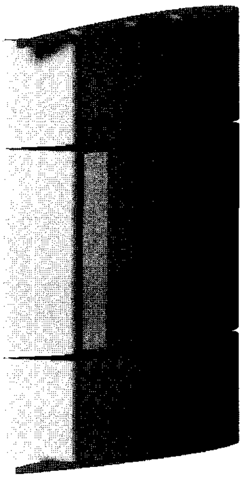

Figure 1: Configurations of rudder model

The effect of the water jet in the flow field can be investigated through an important factor, the jet momentum coefficient, which is defined by the following equation (1). This coefficient has been used mainly for a wing with a finite aspect ratio.

$$C_j = \frac{hV_j^2}{1/2U_\infty^2 c} \tag{1}$$

Where h is the slot height (m) for the jet ejection, c is the chord length (m), V_j is the jet velocity ($m/\sec$) from the slot. Concerning the towing speed and the capability of the jet generating device, the jet momentum coefficient used in the experiments was selected. Also on the basis of previous research by Englar(1975), C_j is selected to be 0.04, corresponding to the critical jet momentum coefficient in the boundary layer control. In this case, the slot height becomes $1(mm)$ and the towing speed is $0.71(m/\sec)$. The water jet was ejected on the flap surface tangentially(Ahn and Kim 1999). The test was carried out by varying the angle of attack at given fixed flap angle. At the fixed flap angle of 40 deg., figure 2 shows the measured lift coefficients.

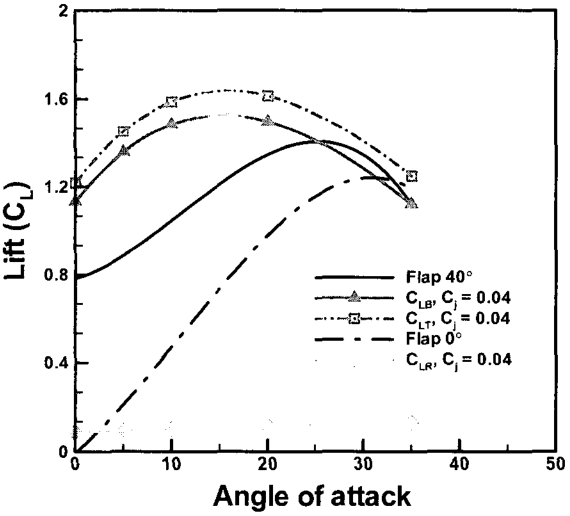

Figure 2: Effect of jet ejection on flap surface with 40 deg. of flap angle in generating lift force

The measured lift coefficient can be decomposed into two parts, as shown in equation (2) below.

$$C_{LT} = C_{LB} + C_{LR} \tag{2}$$

Here, C_{LT} is the total measurement lift obtained from the experiment, C_{LB} is the hydrodynamic contribution that present the pressure lift modified by the pressure peaks caused by water jet ejection, and C_{LR} is the jet reaction force components due to the jet issuing along the flap, which is obtained from the simple calculation considering the jet ejection angle and flux(Wilson and Kerckzek 1979). Through figure 2, it is easily found out that the lift increase appears remarkably despite the exclusion of the jet momentum contribution effect. Also, the amount of maximum lift without jet at the stall angle can be obtained at the lower angle of attack with jet.

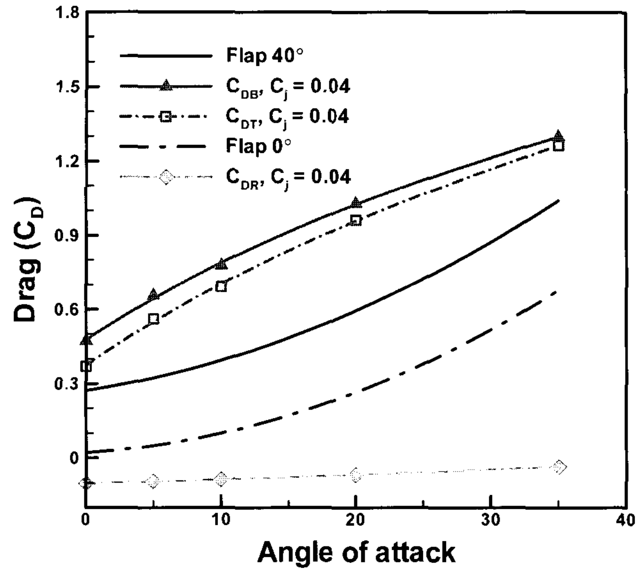

Figure 3: Effect of jet ejection on flap surface with 40 deg. of flap angle in inducing drag force

The same technique was applied to the drag case, such as equation (3).

$$C_{DT} = C_{DB} + C_{DR} \tag{3}$$

The results on drag for cases that considered the jet, the flap only, no flap and no jet are shown in figure 3, respectively.

2.2 A fin model test in cavitation tunnel

From the towing test, it was found that the rudder performance increased remarkably. However, some problems such that of the 3-dimensional effect were generated, and the local flow was difficult to observe. Therefore, to obtain sufficient information about the change in the local flow field between the main foil and the flap, a test, which was expected to show 2-dimensional flow, was carried out in the cavitation tunnel (Ahn 2003). The NACA 0021 model, the same section of the towing test, was used for the cavitation tunnel test, so that the test would be consistent with the towing test. Table 2 summarizes the model size, and figure 4 shows the model installed in the cavitation tunnel.

Table 2: Principal dimensions of fin

NACA0021	Main Foil	Flap
1. Chord (mm)	182	76.3 (30.5%C)
2. Span (mm)	148	148
3. Position of sensing: (30%c) from L.E.		
4. Position of flap hinge: (25%c) from T.E.		
5. Maximum thickness: 21%c		
6. Geometric aspect ratio: 0.592		

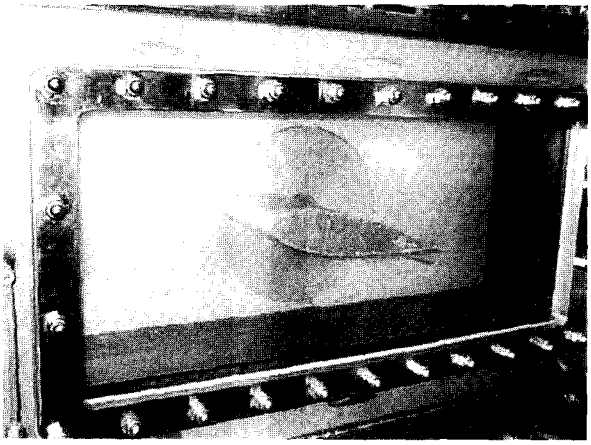

Figure 4: Setup model in C.T. test section

The water flux ejected from the slot has two cases by $6.6(kg/\sec)$ and $13.2(kg/\sec)$. The test condition was such that the angle of attack was fixed to 0, 15, 20, 25 deg. and the flap angle was varied by 0, 20, 40 deg for a given angle of attack. In these cases, the lift and the drag, and the moment were measured separately through post-processing of some of the raw data. Figure 5 shows the result about the obtained lift at the given fixed angle of attack 40 deg.. According to the figure 5, C_{LR} the reaction force component due to the jet ejection increases with the increase in the jet momentum coefficient C_j. However, due to the jet ejection, C_{LB} also increases markedly, that is, increasing the jet flux induces the Coanda effect, and this effect, in turn, increases the jet flux along the flap surface simultaneously. Then, the circulation around the flap increases to enhance the lift.

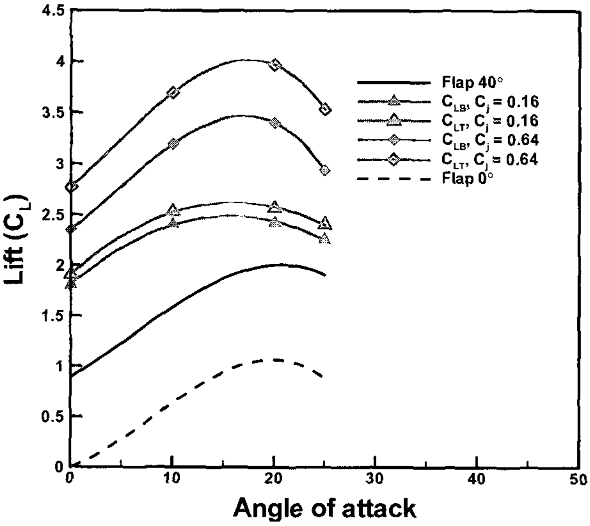

Figure 5: Effect of jet flow rate on lift coefficient at flap angle 40 deg.

In figure 5, especially, when C_j increases from 0.16 to 0.64 at the angle of attack of 0 deg., the lift coefficient increases by 164%.

According to the above results, although others factors such as the drag, the moment, the efficiency, and the pressure center and so on have to be considered in evaluating the whole performance, however, because the main objective of the present study was the improvement of the lift performance, it is thought to be developed remarkably, considering the lifting increasing rate.

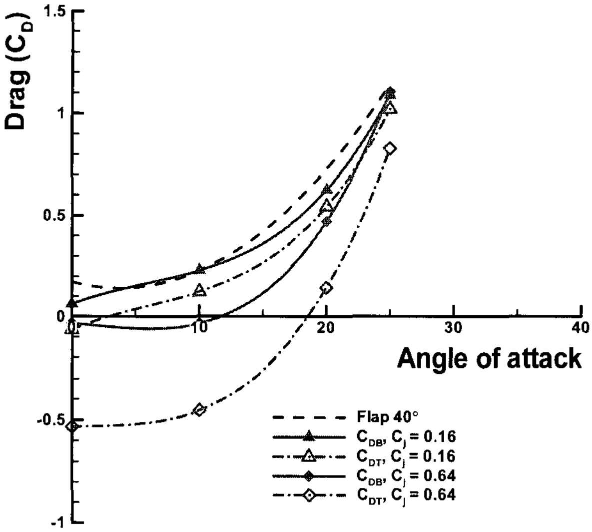

Figure 6: Effect of jet flow rate on drag coefficient at flap angle 40 deg.

Figure 6 shows the results of drag. The measured drag C_{DT} and C_{DB} considering the exclusion of the jet reaction effect is shown together. According to this figure, the propulsion effect is noted. In other words, because of the jet ejection, the form drag can be decreased to less than even that of the case with no jet.

2.3 Investigation of equivalent lift-drag ratio

Due to the water jet ejection, the form drag decreases significantly; however, we must consider the merits of the jet ejection accounting for the consumption power. The drag coefficient C_D has negative values in special conditions, namely, those conditions at which a propulsion effect appears. According to the results mentioned above, because these negative coefficients are obtained by the power consumption, the equivalent lift-drag ratio C_{De} should be considered. Especially in the blown flap, because the equivalent lift-drag ratio is one of the most important factors that decides the foil performances, the C_{De} must take into consideration the consumption energy as well as the form drag. Therefore, the efficiency can be expressed by using the equivalent drag. According to Williams et al (1963), the equivalent drag is defined as follows (4).

$$D_e = D_P + D_i + D_{pump} + D_{ram} \tag{4}$$

Here, D_e is the equivalent drag, D_P is the form drag, D_i is the induced drag, D_{pump} is the power for driving pump, divided by the inflow speed, and D_{ram} is the drag, concerned with the momentum responsible for maintaining the influx from the outside, which can be expressed as $\rho Q U_\infty$.

$$C_{De} = C_{Dmeas} + \frac{1}{2} C_j \frac{V_j}{U_\infty} + C_j \frac{U_\infty}{V_j} \tag{5}$$

D_p and D_i can be directly obtained by experiment, so they are summed to be written as $D_{meas.}$. Therefore, modifying, nondimensionalizing and simplifying equation (4), it will be rewritten as equation (5).

Figure 7 shows the equivalent lift-drag ratio, which determines the efficiency of this system. Compared with the case of no jet, the case with jet injection showed that the equivalent lift-drag ratio increased slightly except for the case of C_j, 0.64. But when C_j is 0.16, the amount of maximum lift seems to increase obviously at the similar equivalent lift-drag ratio compared with that of the no jet case. In addition, the inside of circle in the figure 7 shows that the jet increases as jet injects at the same equivalent lift-drag ratio.

According to the results mentioned above, the desirable lift performance could be obtained if the ejected jet fluxes are controlled appropriately by the existing state of several conditions.

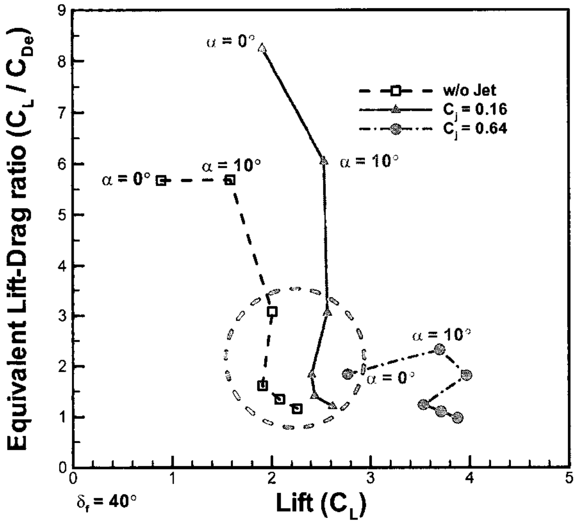

Figure 7: Equivalent lift-drag ratio at flap angle 40 deg.

2.4 Investigation of local flow field

As we have seen from the tests and their results, the increase of lift and the decrease of form drag can be estimated, but they are just results obtained from the global viewpoint. And just explaining the physical background is insufficient to describe the reason of the increase or decrease of lift and drag. Therefore, the local flow measurement and observation will make it possible to recognize the physical meaning of the increase and decrease. First, in order to know the local difference between the pressure side and the suction side when the jet was ejected from the slot to the flap surface tangentially, the surface pressure measurement was carried out.

Figure 8 shows the result of surface pressure measurements and CFD simulation for a flap angle of 20 deg., C_j of 0.16. From this figure, the physical phenomenon was well explained qualitatively, even if each result did not exactly agree with each other quantitatively.

However, the CFD simulation expects the pressure peaks exactly which is hard to detect as an experiment at the 25%c where the water jet is ejected. Therefore, it might be concluded that the CFD simulation is available for the explanation of the flow phenomena.

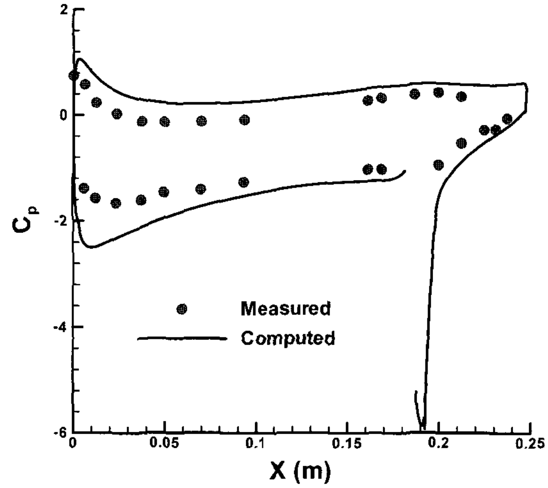

Figure 8: Evaluation of computed C_p distribution around the foil at 20 deg. of flap angle under jet flow rate C_j=0.16

Table 3: Comparison of C_L value between computed and experiment

(α, δ, Cμ)	Computed	Measured
(0, 20, 0)	0.62±0.022	0.56
(0, 20, 0.16)	1.97	1.20
(0, 20, 0.64)	2.96	2.09
(10, 20, 0)	1.47±0.008	1.48
(10, 20, 0.16)	3.08	2.20
(10, 20, 0.64)	4.33	3.33

In table 3, the CFD result using FLUENT is compared with the obtained result from the experiment. When the model was in the inflow, on the state of fixed flap angle 20 deg. in the given angle of attack 0 deg., the unsteady oscillation was detected in the wake sheet passed through the trailing edge. This seems to be an unavoidable phase because the model section is NACA 0021 with flap 20 deg. However, as the water jet was ejected, the unsteady phenomenon disappeared.

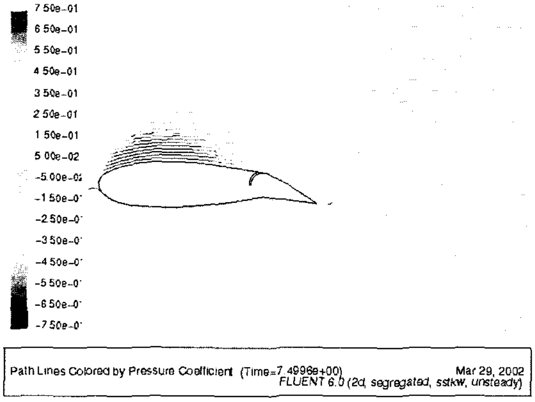

Figure 9: Flow filed (without jet)

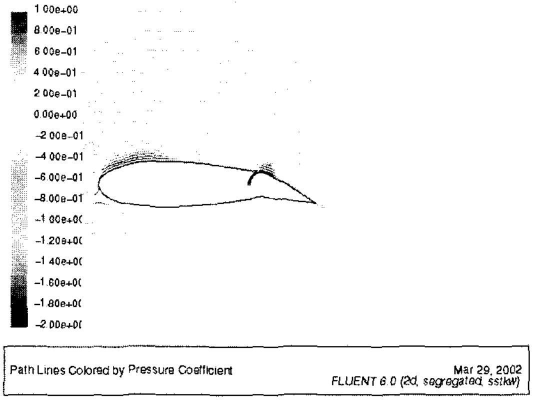

Figure 10: Flow filed (with jet)

The above phenomenon is explained clearly in figures 9 and10. That is, the ejection of the water jet eliminates the unsteady oscillation phenomenon. In addition, especially from the figure 10, it is clear that water jet blowing makes the difference of C_P between the suction side and pressure side increase, consequently, the increase of C_P makes the lift increase. It is also estimated that the water jet ejection can make the wake sheet be extended in a straight line to the far downstream. Because of this extension, the noise problem induced from the vortex is expected to be solved.

3 Conclusions

A flapped rudder and a fin device which can eject a water jet were designed and manufactured, and tested in the towing tank and the cavitation tunnel, respectively. The lift is increased due to the Coanda effect. The lifting device with the flap can be developed for 2-dimensional and 3-dimensional flows. The local flow measurements and CFD simulation were carried out, so the changes of physical phenomenon due to the water jet were observed. Based on the CFD result, we can conclude that the noise and oscillation induced by the unsteady flow due to the flap in the wake field can be eliminated by the water jet ejection. In addition, in all of the cases, the lifting devices can be developed by the lift increase due to the water jet so that it will be practically used in marine control. Consequently, future research on reasonable water jet generating mechanism, coupling linkage system for the flap and water jet ejection, the interference with the propulsor and the rudder can be useful in developing a the highly efficient rudder and fin system applicable for practical field.

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